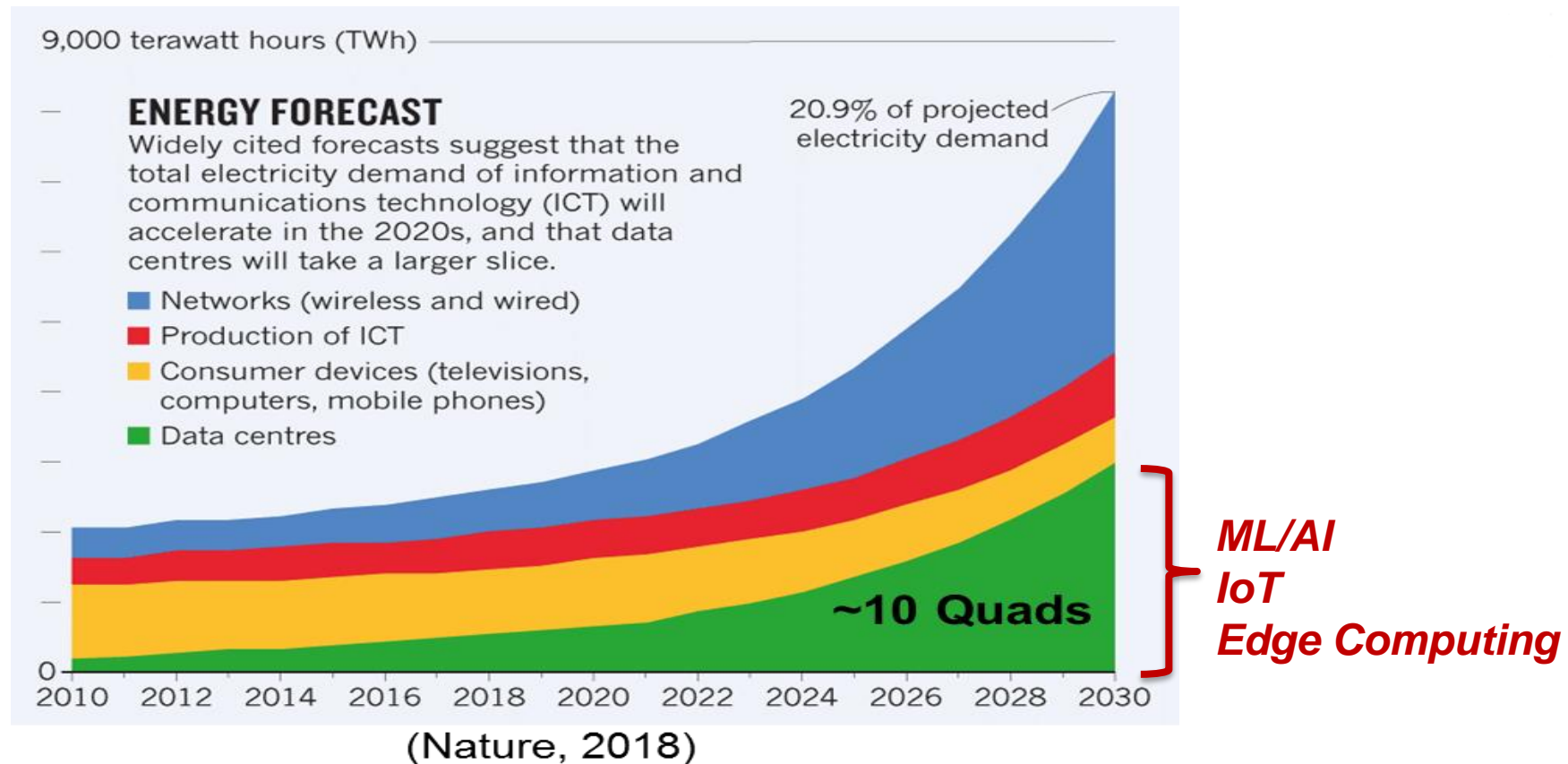


# Analog Computing: Back to the Future?

Michael Haney  
Program Director



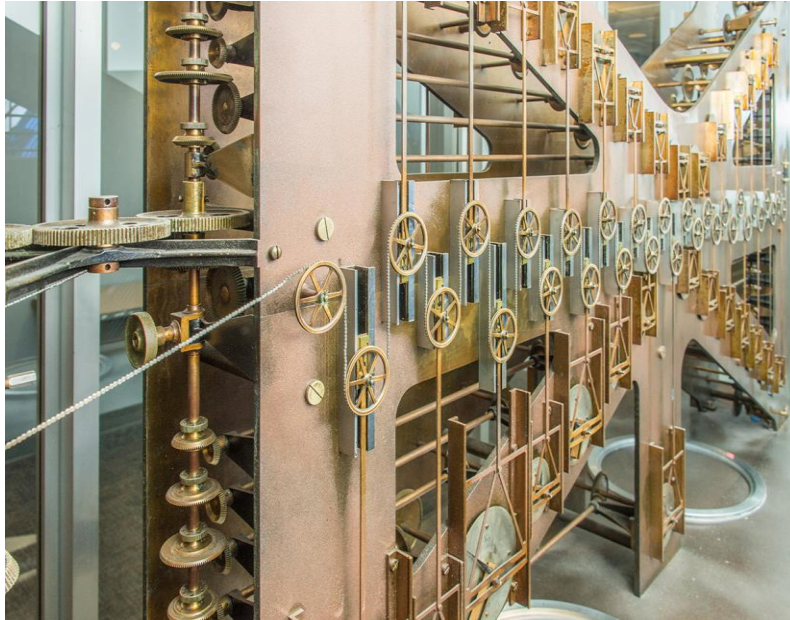
# Motivation



- Scaling of Si-based digital computing is coming to an end.
- Can energy-efficient Analog Computing be transformative?

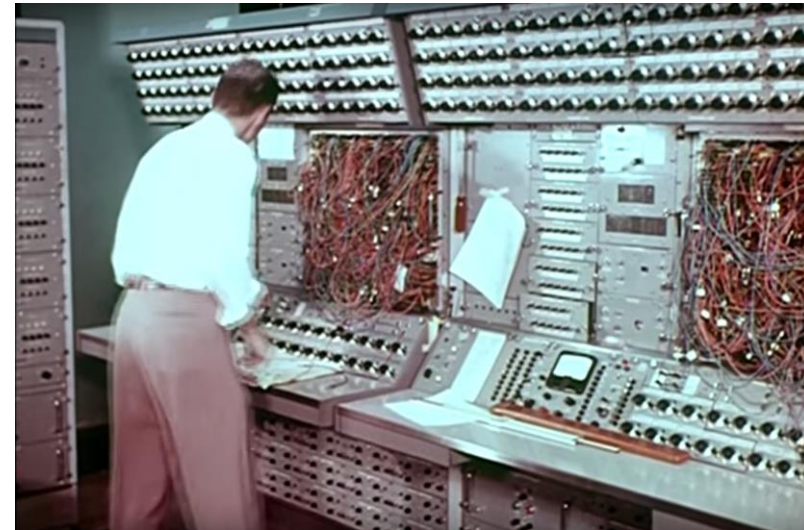
# Original “Modern” Analog Computers

## Mechanical embodiments (1800's – 1960's)



**US Tide Predicting Machine No. 2  
“Old Brass Brains”  
(1910-1965)**

## Electronic embodiments (1940's-1970's)



**X-15 simulator analog computer  
(1960's)**



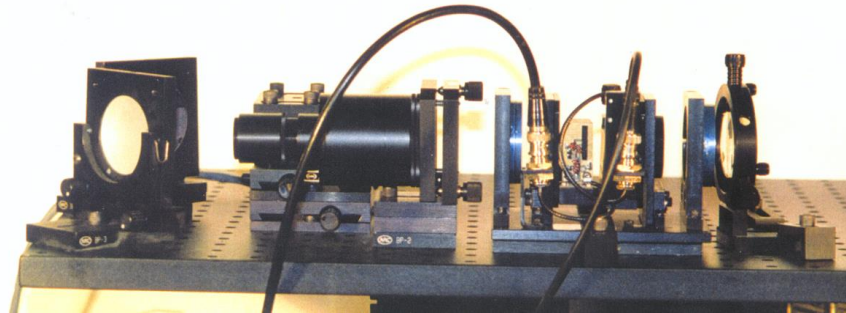
# What happened?

Digital Computing took over....

50 years+ of **Moore's Law** scaling:  $\sim 2x$  in operations/J every 1.5 years

**Example:**  $\sim 1990$  RAPID SAR DARPA project:

Real-time Acousto-optic Programmable Imaging and Display for SAR

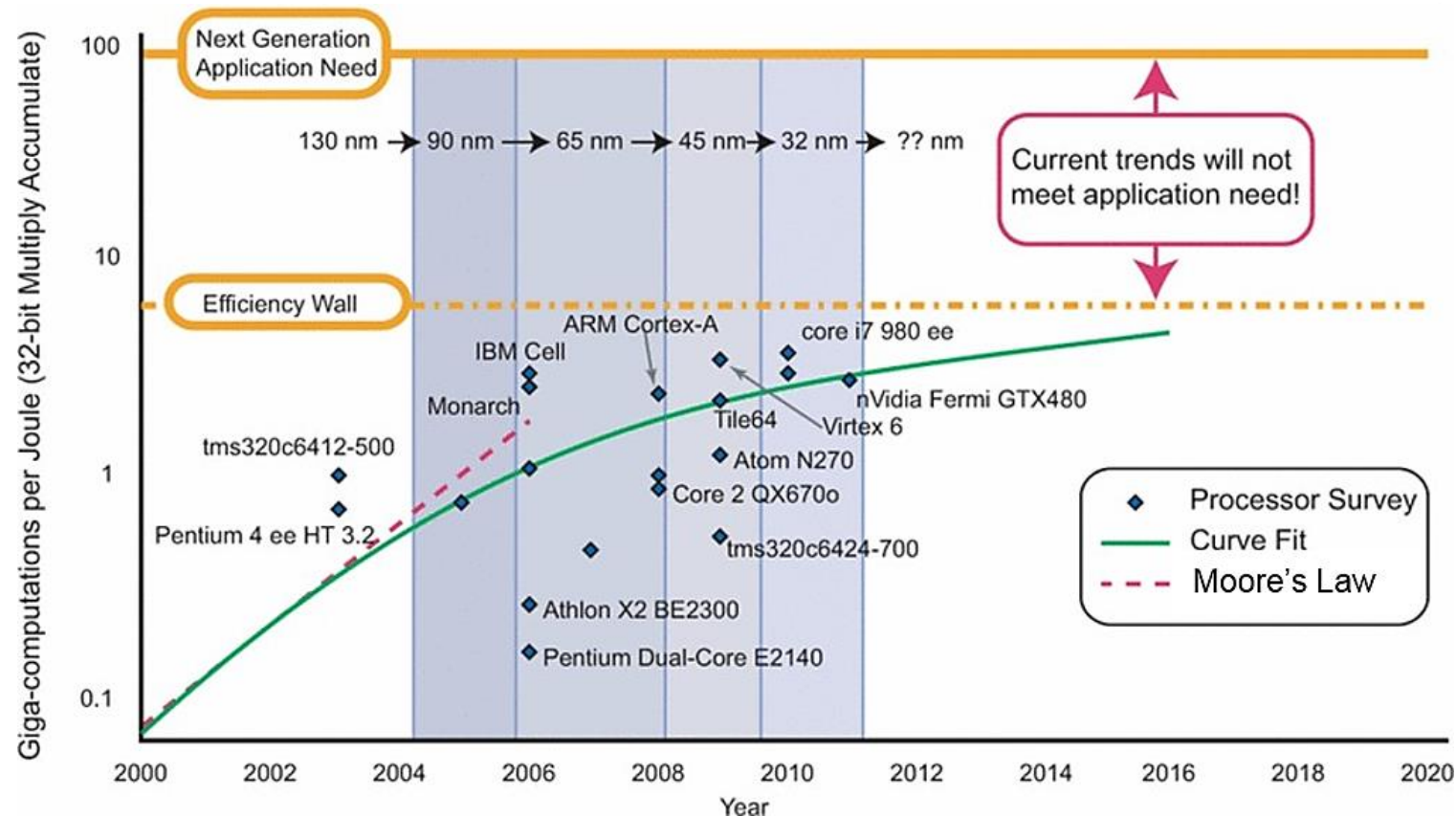


In 1990:  $\sim 100W$  analog vs.  $10kW$  digital  $\rightarrow$  **100x more efficient!**

In 2000:  $\sim 100W$  analog vs.  $\sim 100W$  digital!  $\rightarrow$  **Not any better!**

**However,  $\sim 20$  years later ...**

# Computing Efficiency Reaching Limits



## End of "Moore's Law"

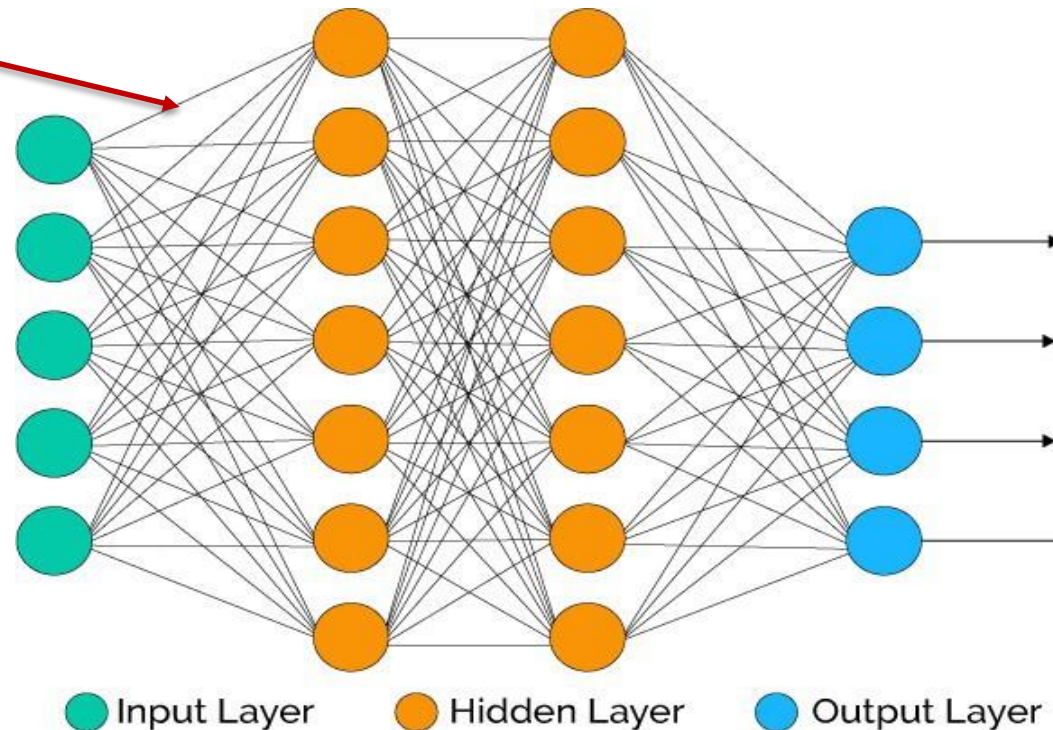
- Physical limits (Gate oxide ~ 5 Si atoms thick; electron tunneling; leakage current).

# Opportunity for Analog Computers?

## Artificial Neural Networks

- Basis of Artificial Intelligence applied to surge in Machine Learning workloads
- Similar to the learning and inference processes of a brain

The connections are analog: each line is assigned a weight that can represent a real number.

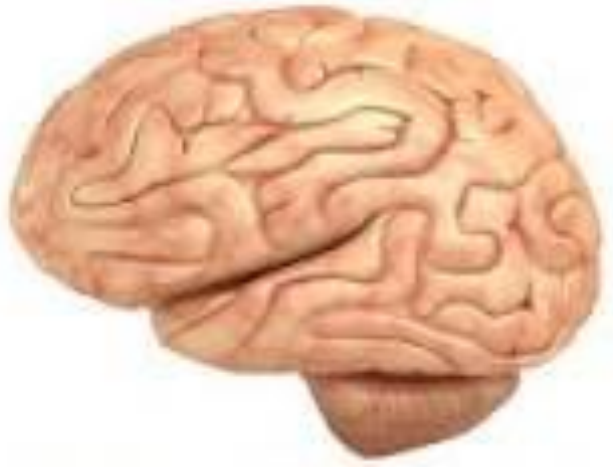


Currently based on digital hardware –

What if the hardware was *analog*?

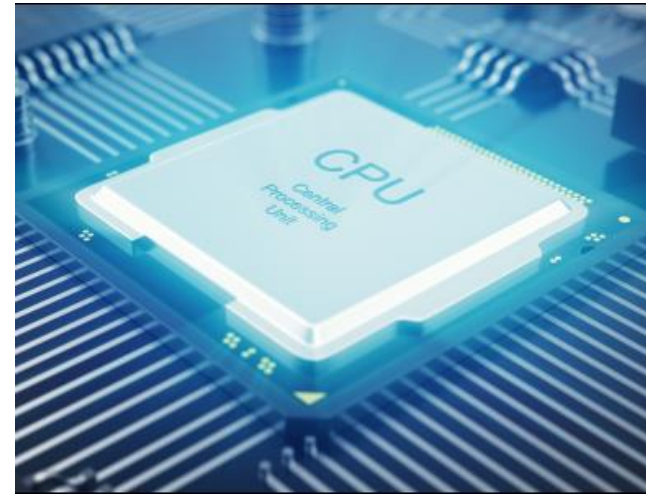
# Opportunity for Analog Computers?

*Analog*



$3 \times 10^{14}$  “OPS”/W

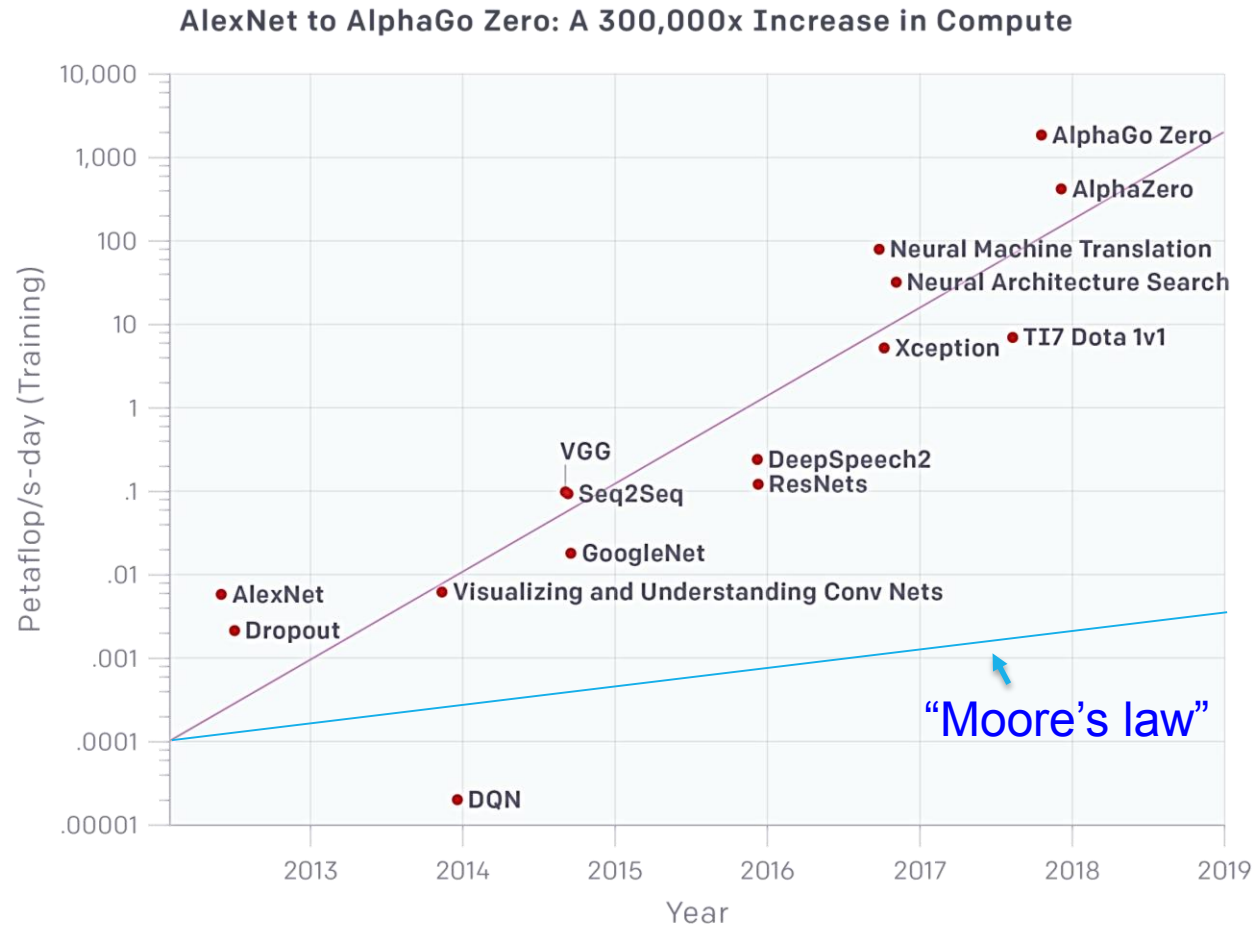
*Digital*



$6 \times 10^8$  FLOPS/W

Best commercial digital processor are ~1,000,000x less energy efficient as the biological brain.

# Increase in AI Workloads



Source: [www.openAI.com](http://www.openAI.com)

- ML: 300,000X increase in compute since 2012
- Moore’s Law: 12X increase



# Does the “end of Moore’s Law” provide an opportunity for ANN Analog Computing?

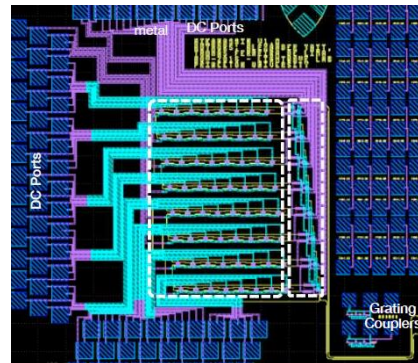
## Electronic

- Resurgence in Analog Artificial NNs computation and memory circuit research.

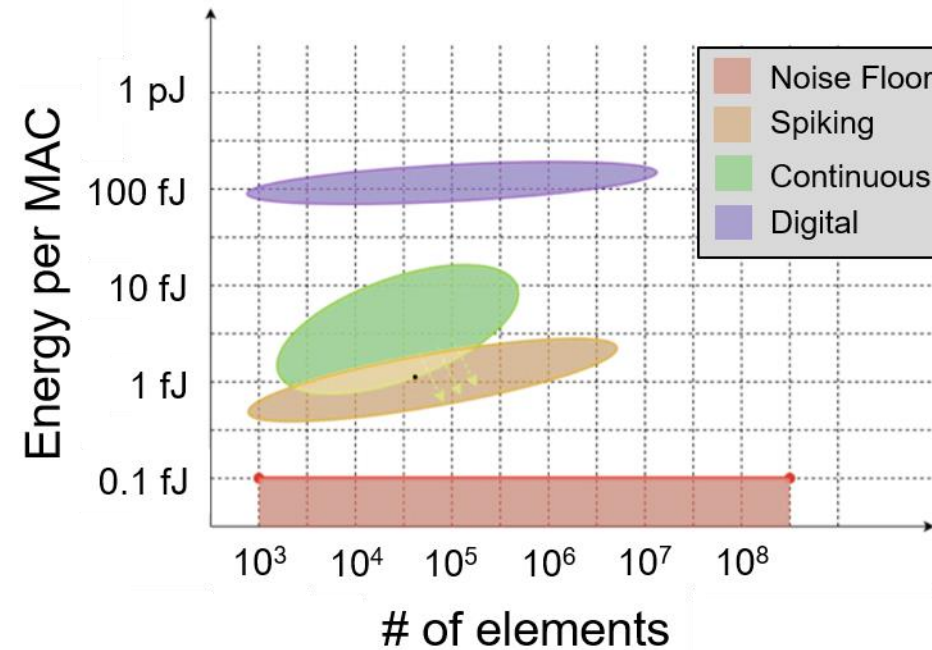
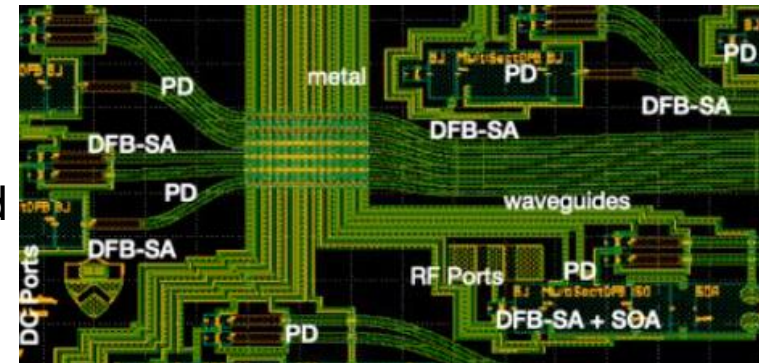
## Optical/Integrated Photonics

- Photonic ANNs

Feed-Forward  
Fully-Connected  
8x8 (analog)



Fully-  
Connected  
(spiking)



# Analog ANN Computing – Questions to ponder:

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- What are the limits in energy/operation?
- Can we efficiently exploit analog's lower precision?  
How/Where?
- What are the key technical challenges to overcome?
- How much computation can be off-loaded to more efficient analog accelerators
  - In HPCs, now at ~10GFLOPS/W? For which workloads?
  - In DCs, for AI/ML/DL– but are there also more general applications?

**Is it time for a deep dive into deep learning?**

**Acknowledgements:**      **John Qi**  
   **Geoff Short**

***Thank You!***



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